

TG-1: Portable Instrument for Transient PM Measurements

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Overview

- Current PM measurement issues
- Survey of commercially available instrumentation
- Laser Induced Incandescence
- Instrument Development
- Future efforts



Emission regulations have rendered PM emissions low as to be comparable to minimum instrument detectivity

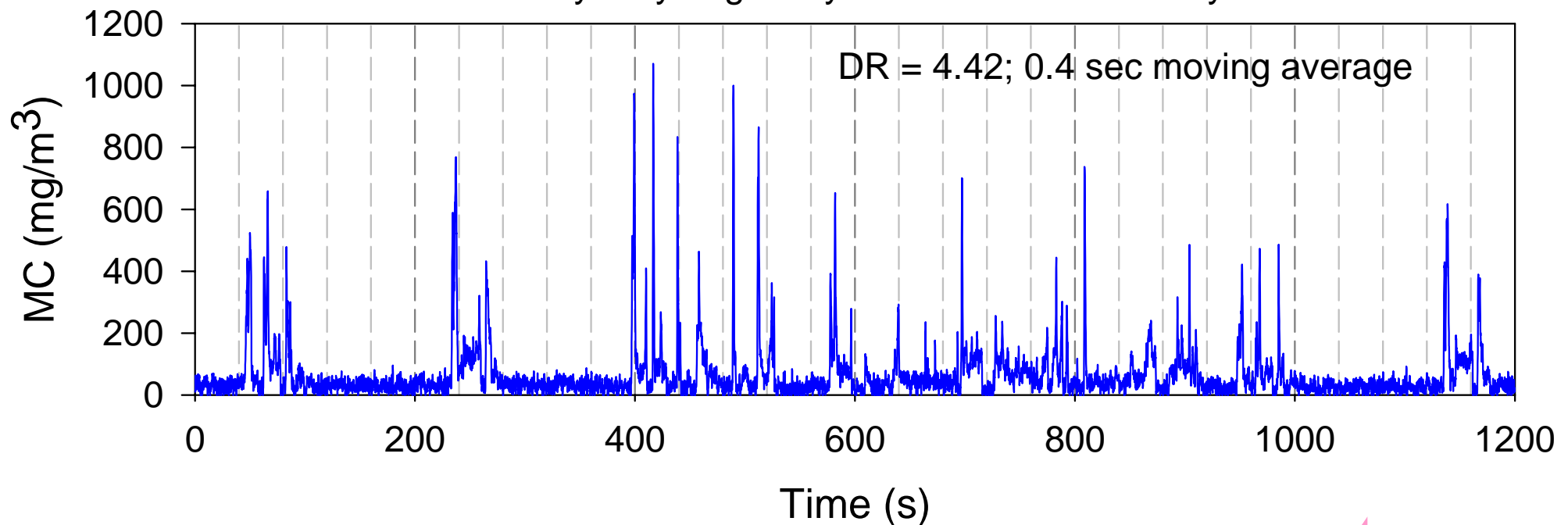
Description	System details	MC (mg/m ³)
N. J. Khatri, John Johnson (1978)	1973 Caterpillar 3150, V-8	27-84
Dave Hoefeldt (1993)	2 cyl Kubota generator set	2-25
Abdul Khalek (1998)	Perkins 4-cylinder	0.4-14
(2003)	Caterpillar's recommendation	0.1

target



Heavy-duty truck emissions regulated based on a transient cycle as well as steady state modes

EPA heavy-duty engine dynamometer transient cycle



Time response $\leq 0.5 \text{ sec}$

Dynamic range $\sim 3\text{-}4$ orders of magnitude

target



Health effects render particle size and number emissions important

Future (EU) regulations are likely to be based on particle number and size.

- Aggregate particle size (D) & number density (N) measurement capability desirable



A survey of available transient PM measurement instrumentation



Instrument	Issues	Cost (Thousands)
Smoke meters	Quantitative measurements not possible	~\$100
TEOM 1105	Yields -ve measurements, vibration sensitive, and coarse resolution	\$24
ELPI	Very coarse resolution	\$70
DMS 500 (Cambustion)	Very expensive	\$190
TG-1 (Argonne)	portable, cross-platform, real-time and modular	\$30

target



Tapered Element Oscillating Microbalance (TEOM)

Tapered Element Oscillating Microbalance

Measures Mass Concentration, M (g/cc) in Diesel Exhausts

$$M = \frac{k_o}{f^2}$$

$$MC = \frac{1}{V} \frac{dM}{dt} = \frac{1}{V} \frac{-2k_o}{f^3} \left(\frac{df}{dt} \right)$$

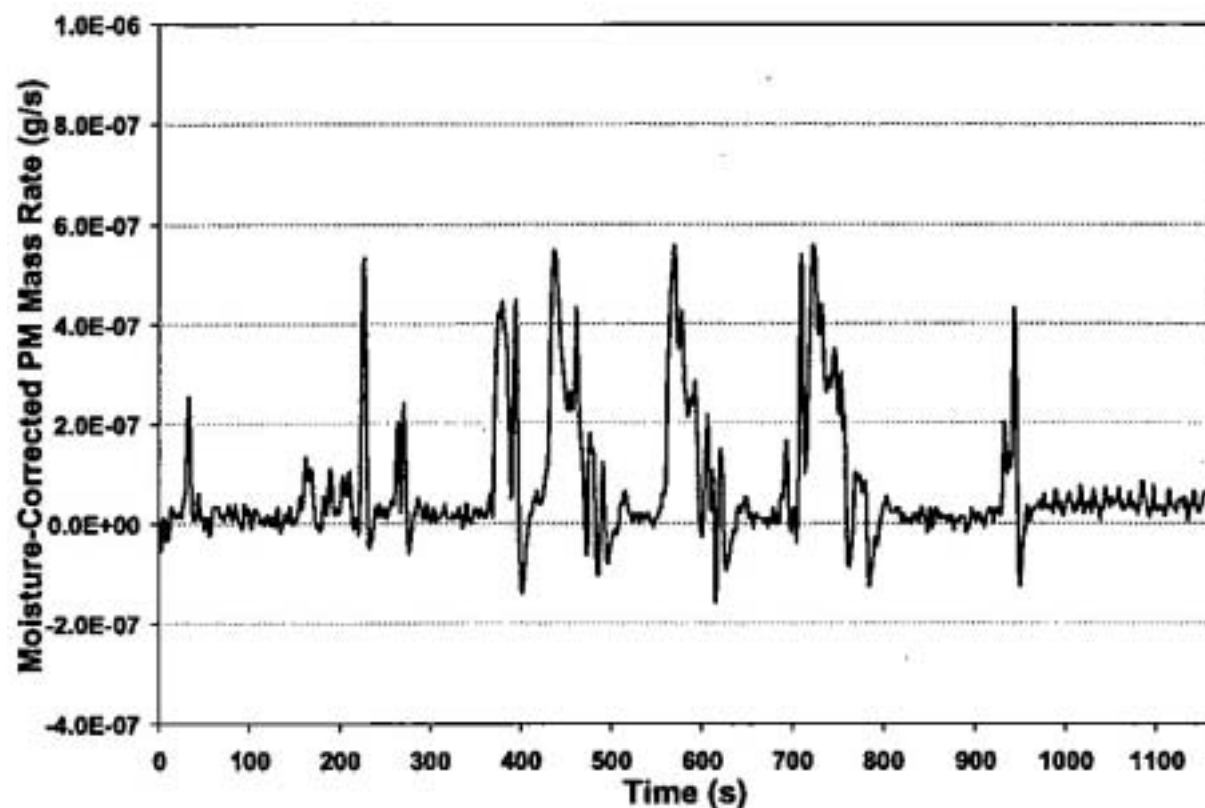
$\therefore f$ as well as $\frac{df}{dt}$ need to be measured accurately.





Measurement issues with TEOM

- Sensitive to typical test-cell vibration levels
- Can yield negative measurements due to water vapor desorption



SAE

2001-01-3575



Laser Induced Incandescence (LII)



LII has many desirable characteristics

- Primarily measures volume fraction

$$f_v \times \rho = MC \text{ (grams/cc)}$$

$$\text{Minimum detectivity} = 0.001 \text{ (mg/m}^3\text{)}$$

- Can measure in real-time

$$\text{Time response/ resolution} = 1\text{e-9 sec/ 0.1 sec}$$

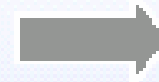
- In combination with Rayleigh scattering yields

$$\text{Mean particle size (nm)} \quad D = K_1 \cdot \left(\frac{Q_{vv}}{MC} \right)^{1/3}$$

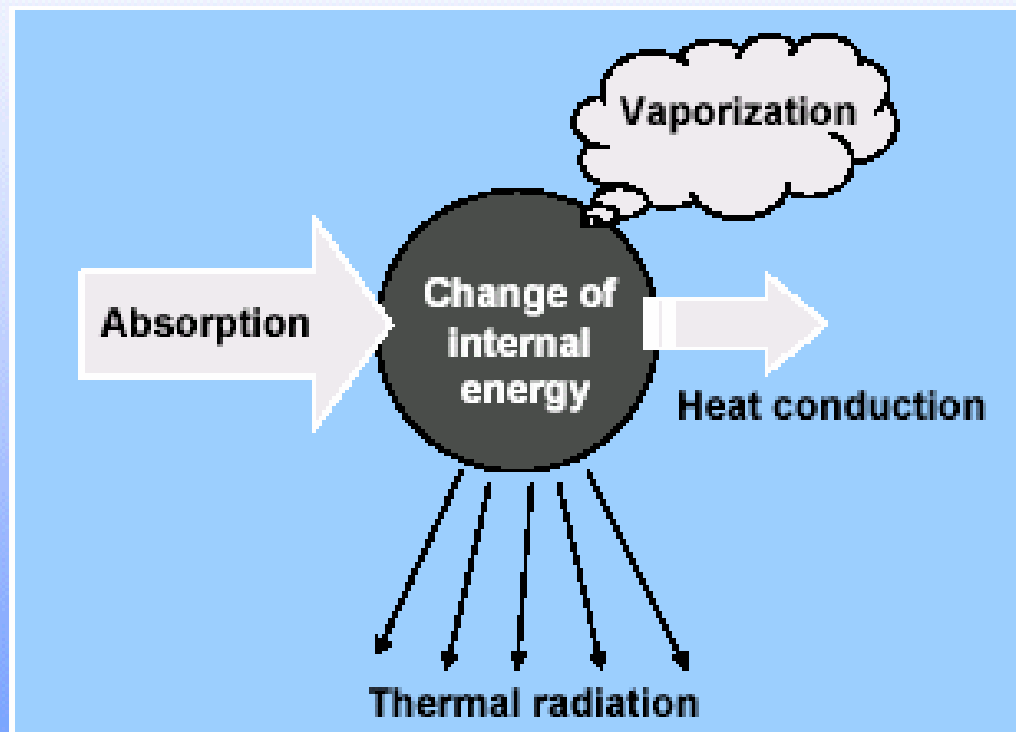
$$\text{Number density (\#/cc)} \quad N = K_2 \cdot \frac{MC}{D}$$

LII phenomenon

Particle heating by means of a highly energetic laser pulse



Detection of the enhanced thermal radiation

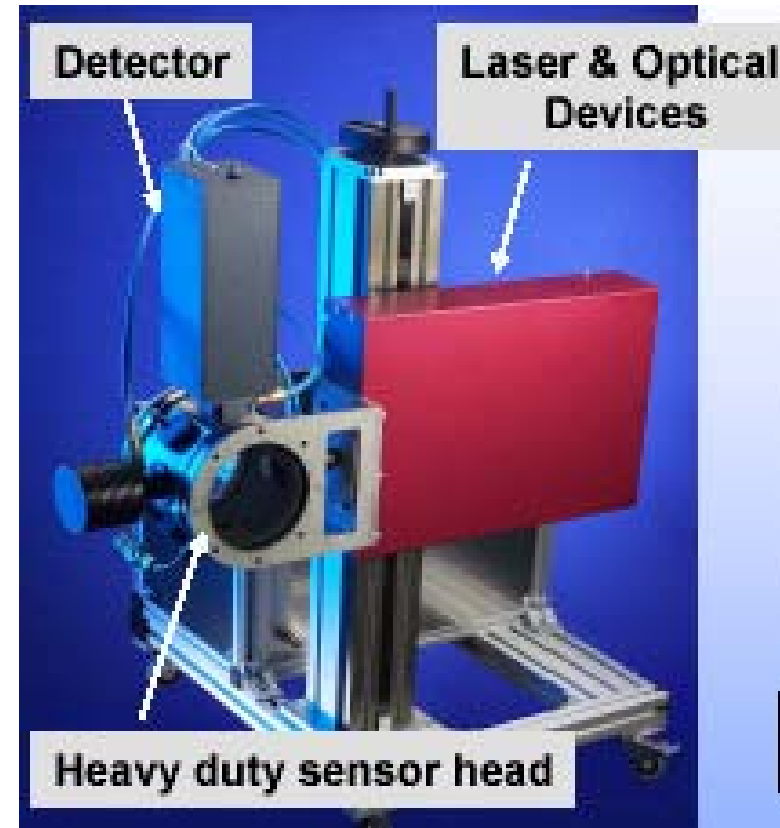
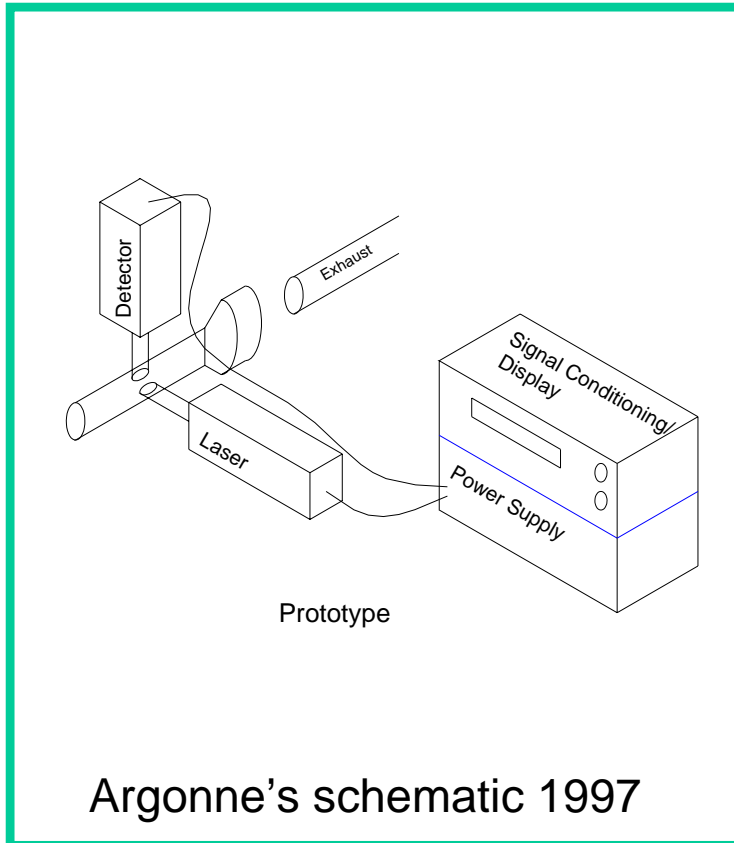


$$\underbrace{Q_{abs} \cdot \frac{\pi d_p^2}{4} \cdot E_i}_{\text{Absorption}} - \underbrace{\Lambda \cdot (T - T_0) \cdot \pi d_p^2}_{\text{Heat conduction}} + \underbrace{\frac{\Delta H_v}{M} \cdot \frac{dm}{dt}}_{\text{Vaporization}} - \underbrace{\pi d_p^2 \int \epsilon(d_p, \lambda) M_\lambda^b(T, \lambda) \cdot d\lambda}_{\text{Thermal radiation}} - \underbrace{\frac{\pi d_p^3}{6} \rho_s \cdot C_s \cdot \frac{dT}{dt}}_{\text{Change of internal energy}} = 0$$



Development of an LII based Instrument

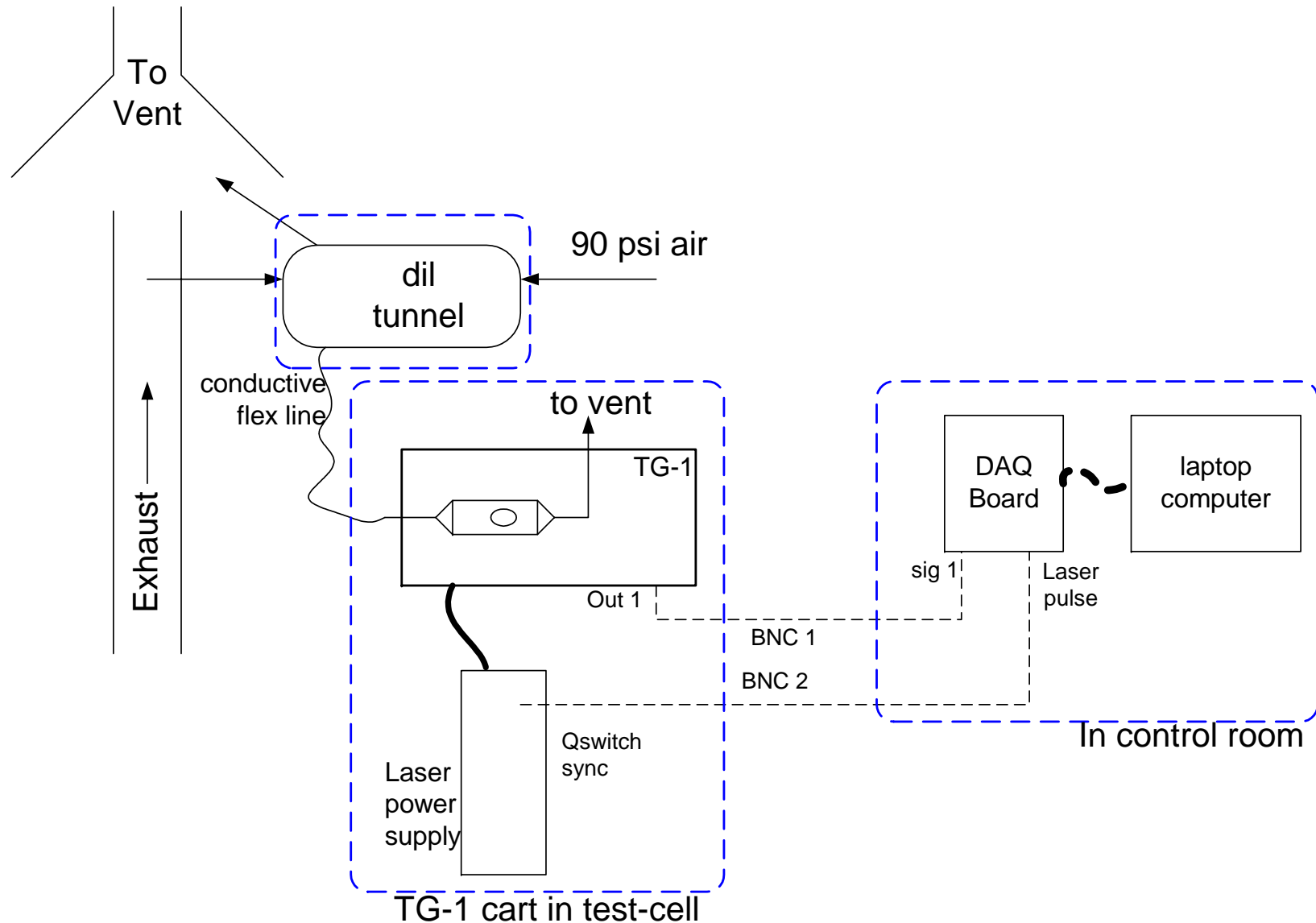
Many possible arrangements were evaluated...



- Sensor head design dependent on engine size
- Potential operator (laser) safety hazard



...to reach an optimal design





A Portable instrument was integrated

Component cost: \$40 K

Size: 24" x 15" x 8.5"

Weight: Approx 40 lbs

Specifications

10 Hz sampling

Utility requirements

110 VAC, 13 Amps



Patent pending



Performance tests on a light-duty diesel engine



Mercedes Benz

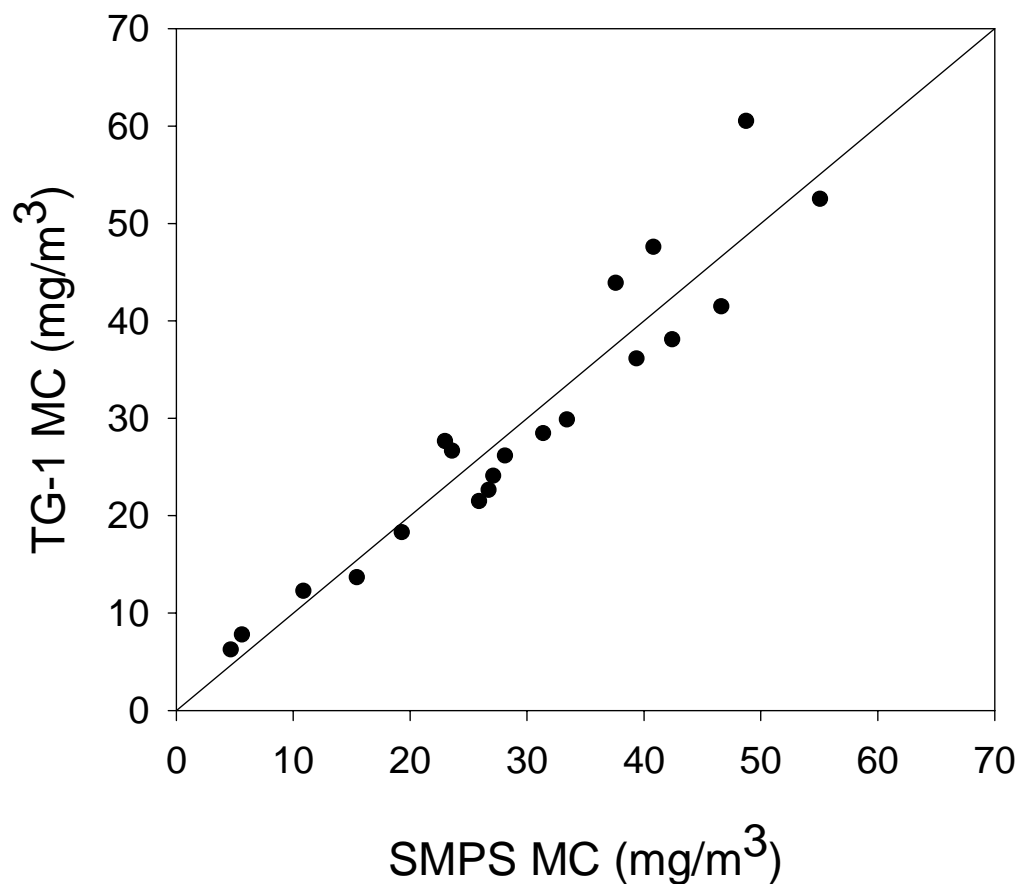
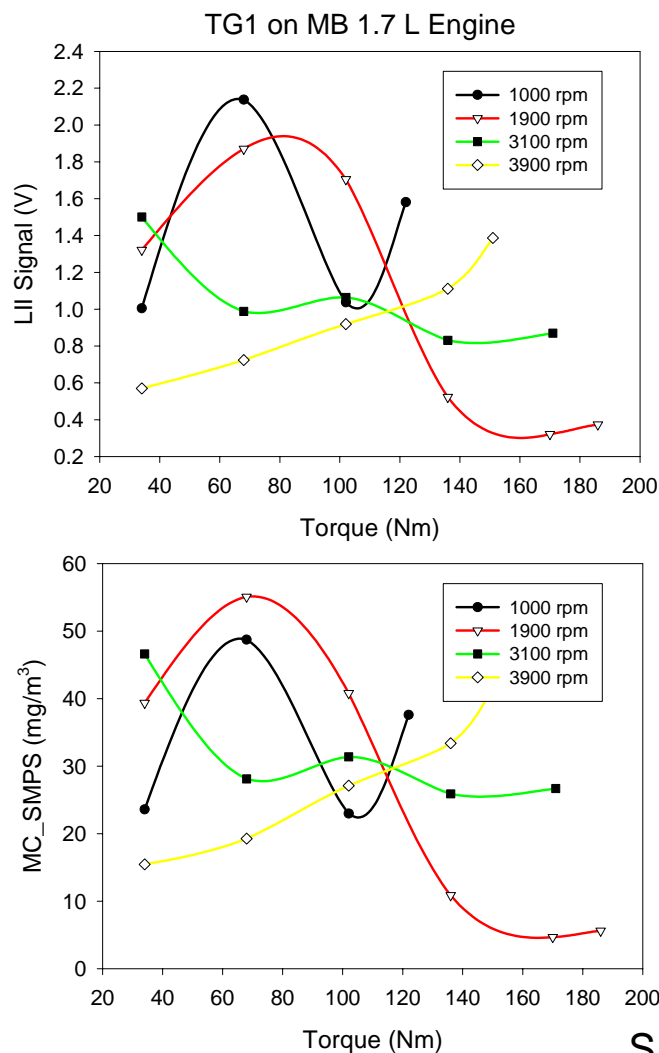
1.7 L

4 cyl

Low-inertia
Dynamometer



Excellent performance over typical diesel engine steady-state operation

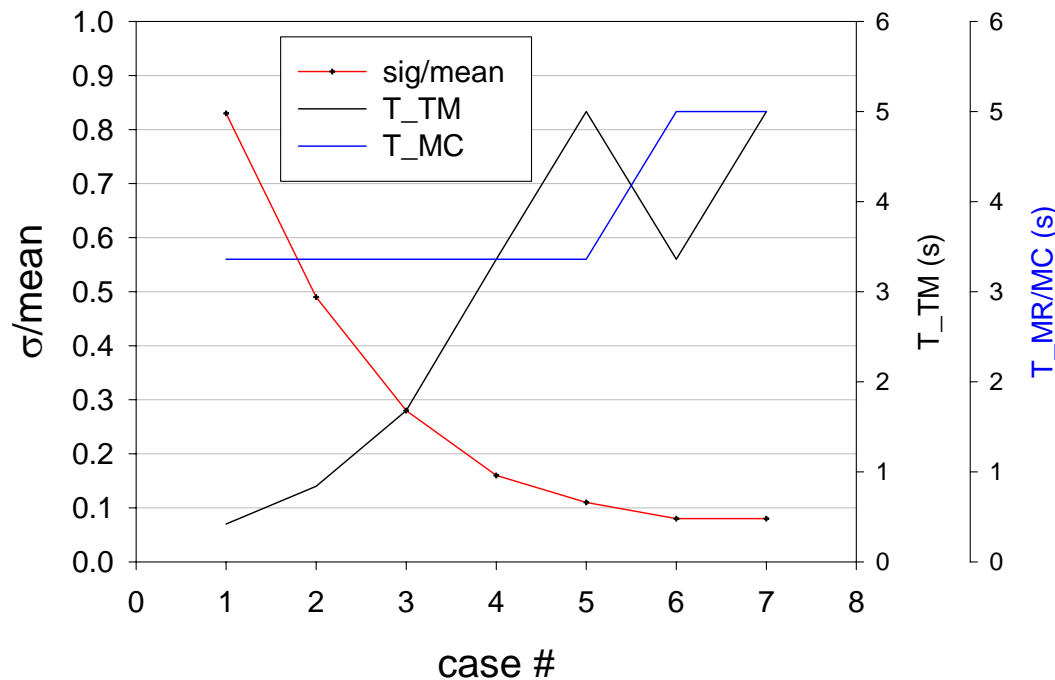


S. Gupta et al.; 6th ETH Conference on Nanoparticle Measurement



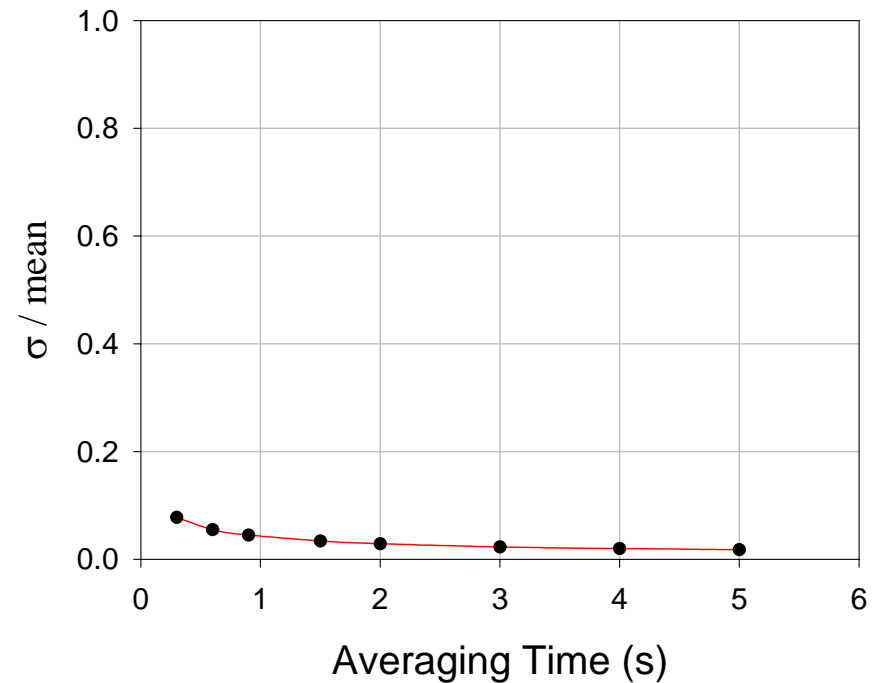
TG-1 has better time resolution than a TEOM 1105

TEOM 1105



5 sec mvg. average

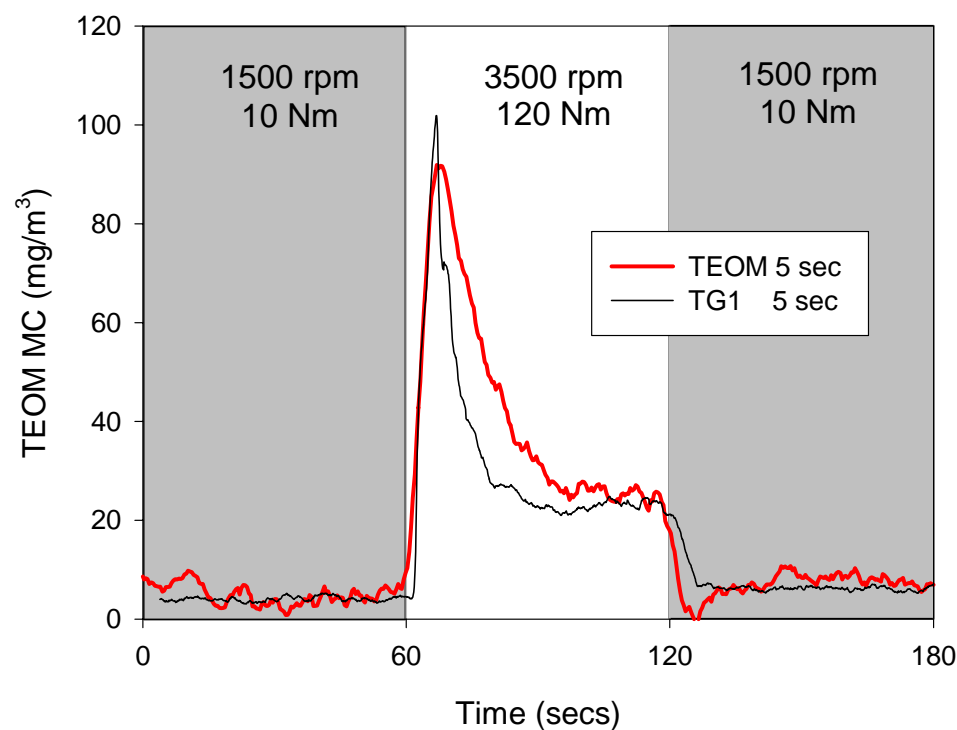
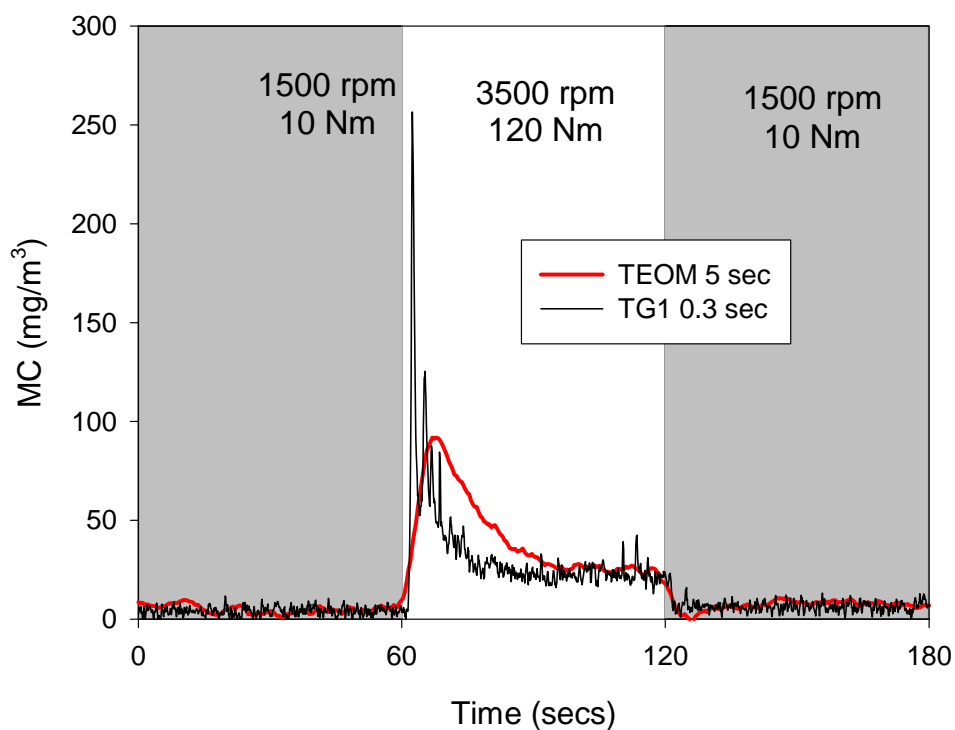
TG-1



0.3 sec mvg. average



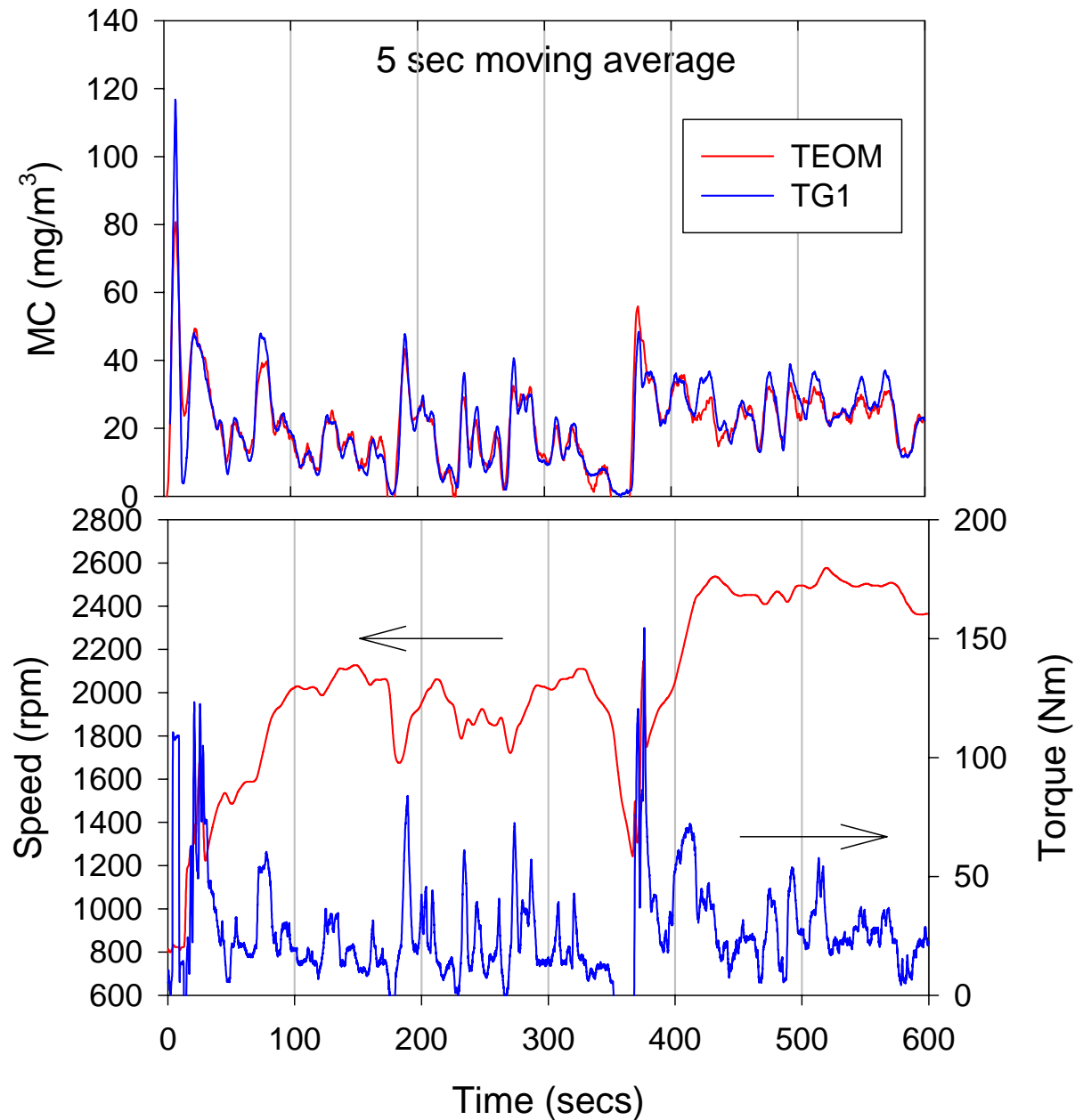
TG-1 performs better than a TEOM 1105 for step changes in engine modes



Transient measurements performed on a Mercedes Benz 1.7 L engine coupled to a low-inertia dynamometer



TG-1 Performance Over the urban driving cycle



Performance tests on a Heavy-duty diesel engine



CAT C-10

6 cyl

10 L

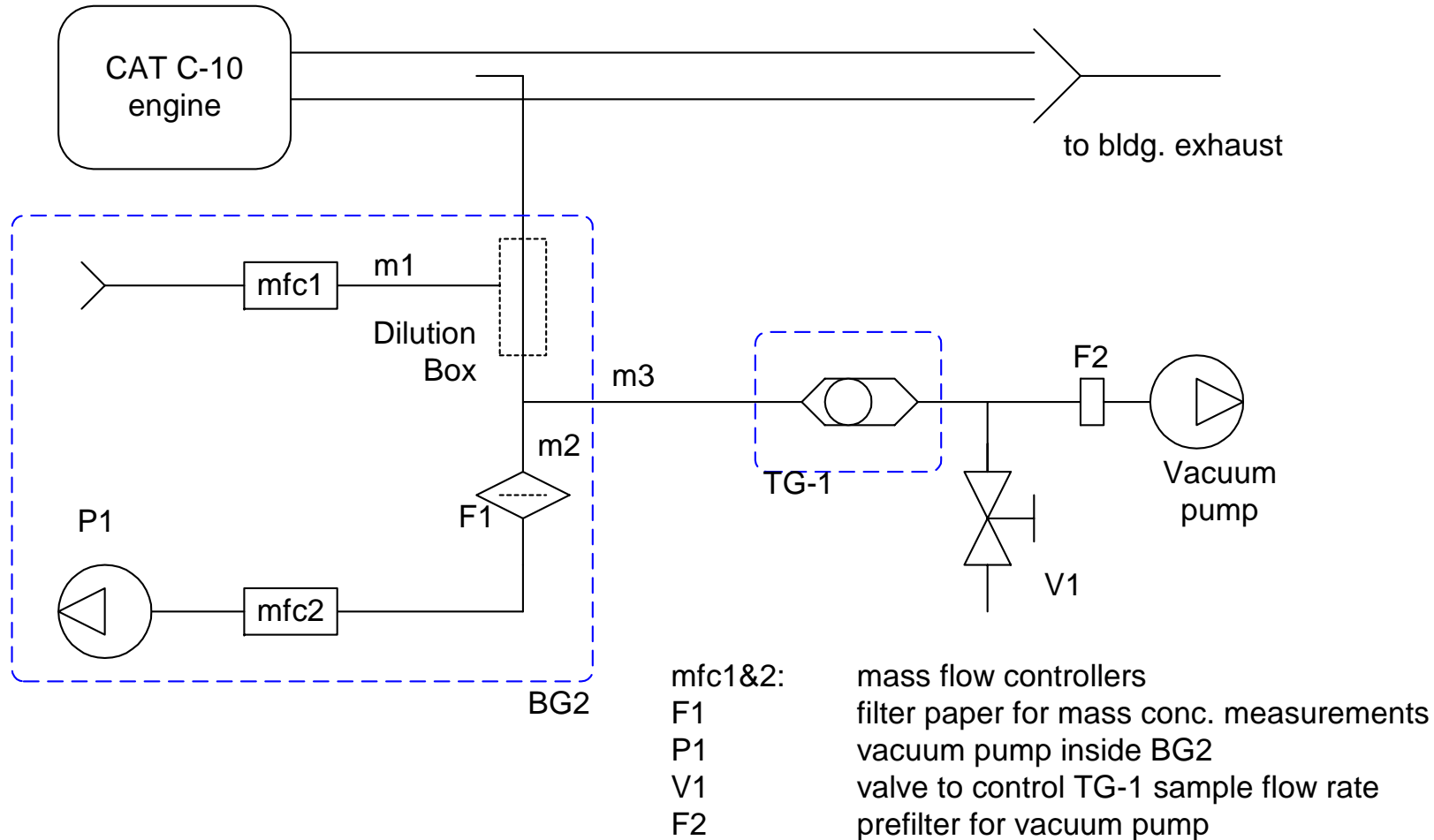
1800 rpm

1460 Nm@

1200 rpm



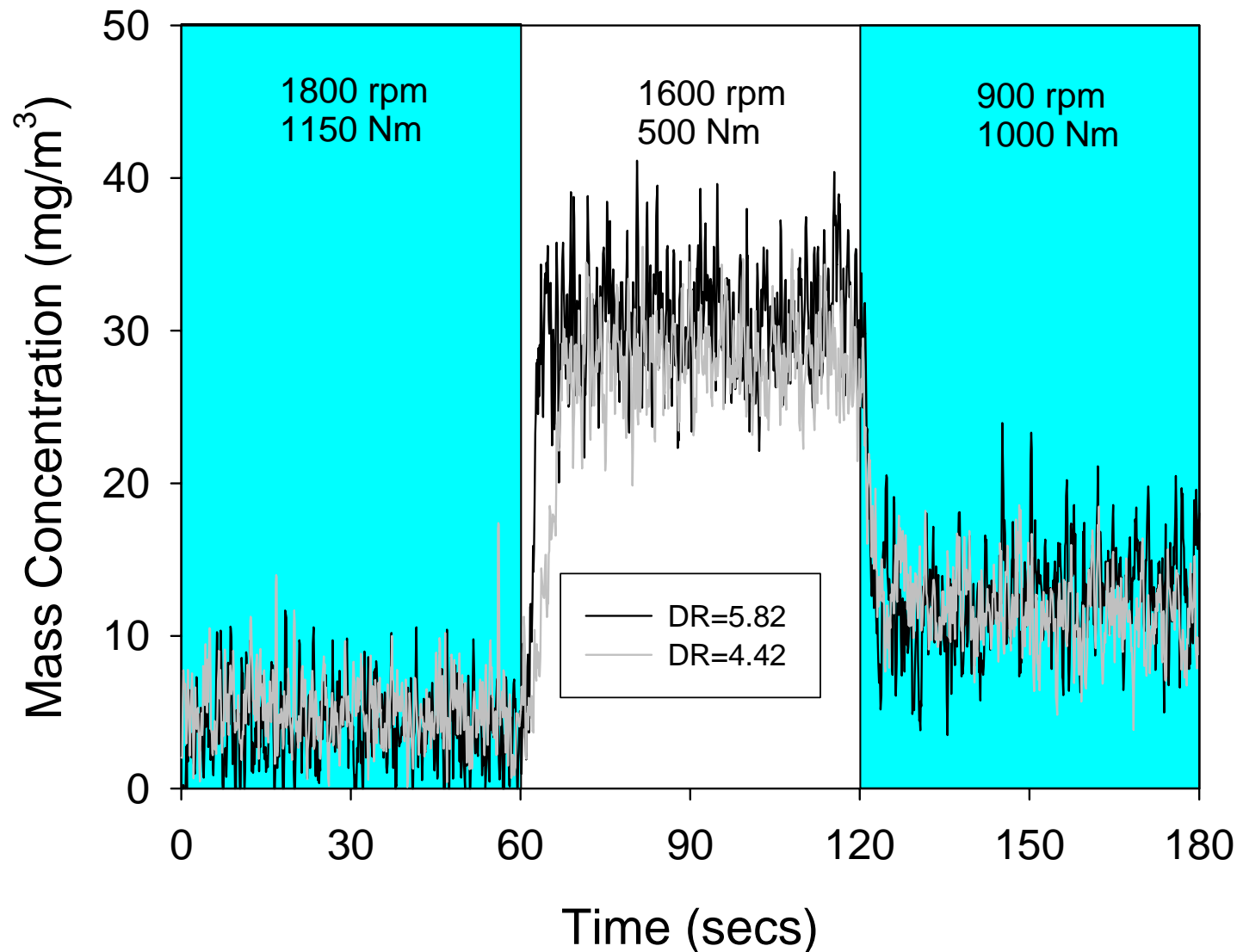
Validation using Sierra's BG2 dilution system



➤ Such a setup necessitated the use of dilution ratios ~ 4 – 8

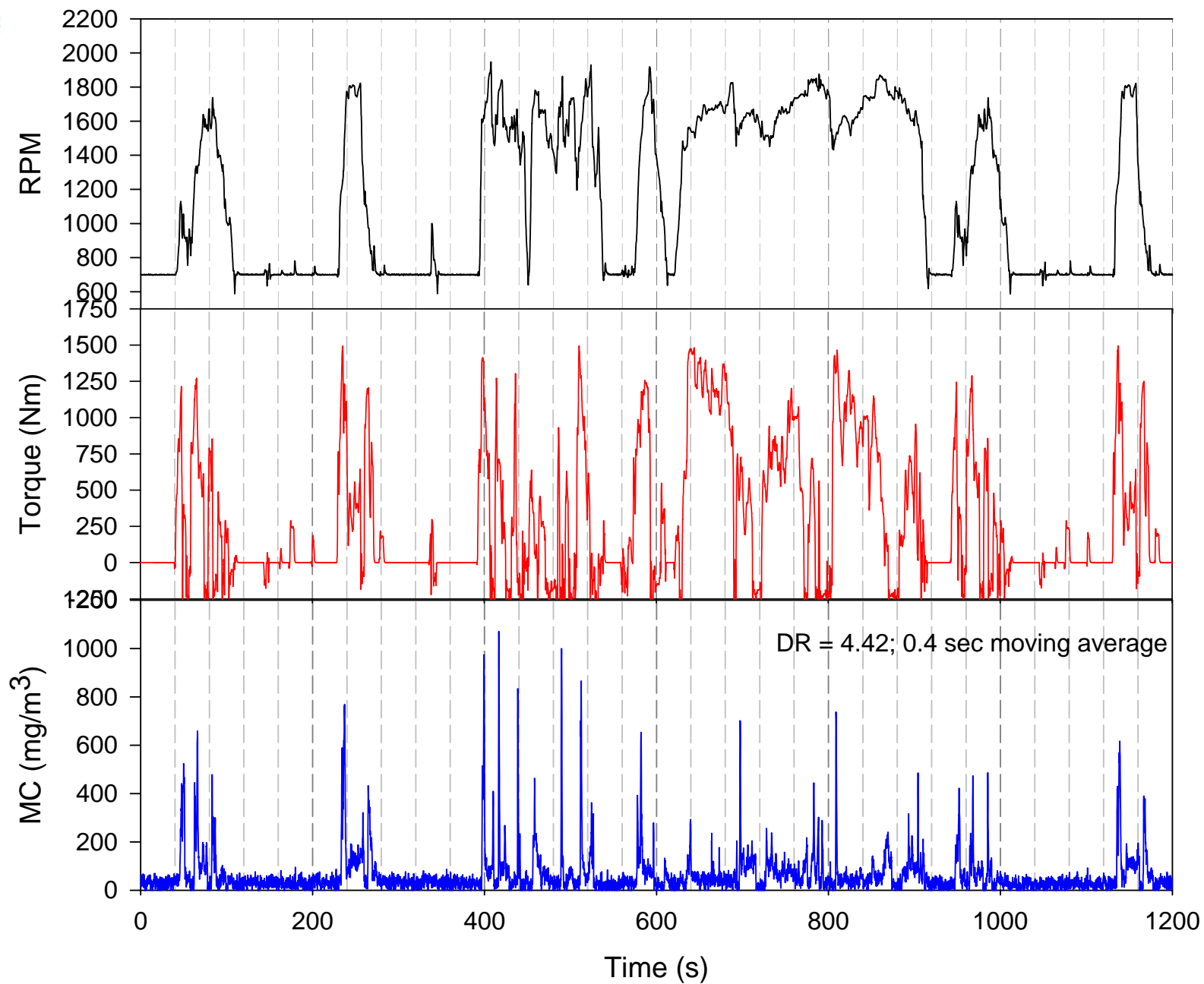


TG-1 has excellent day-to-day repeatability





EPA Heavy-duty Engine Dynamometer Transient Cycle



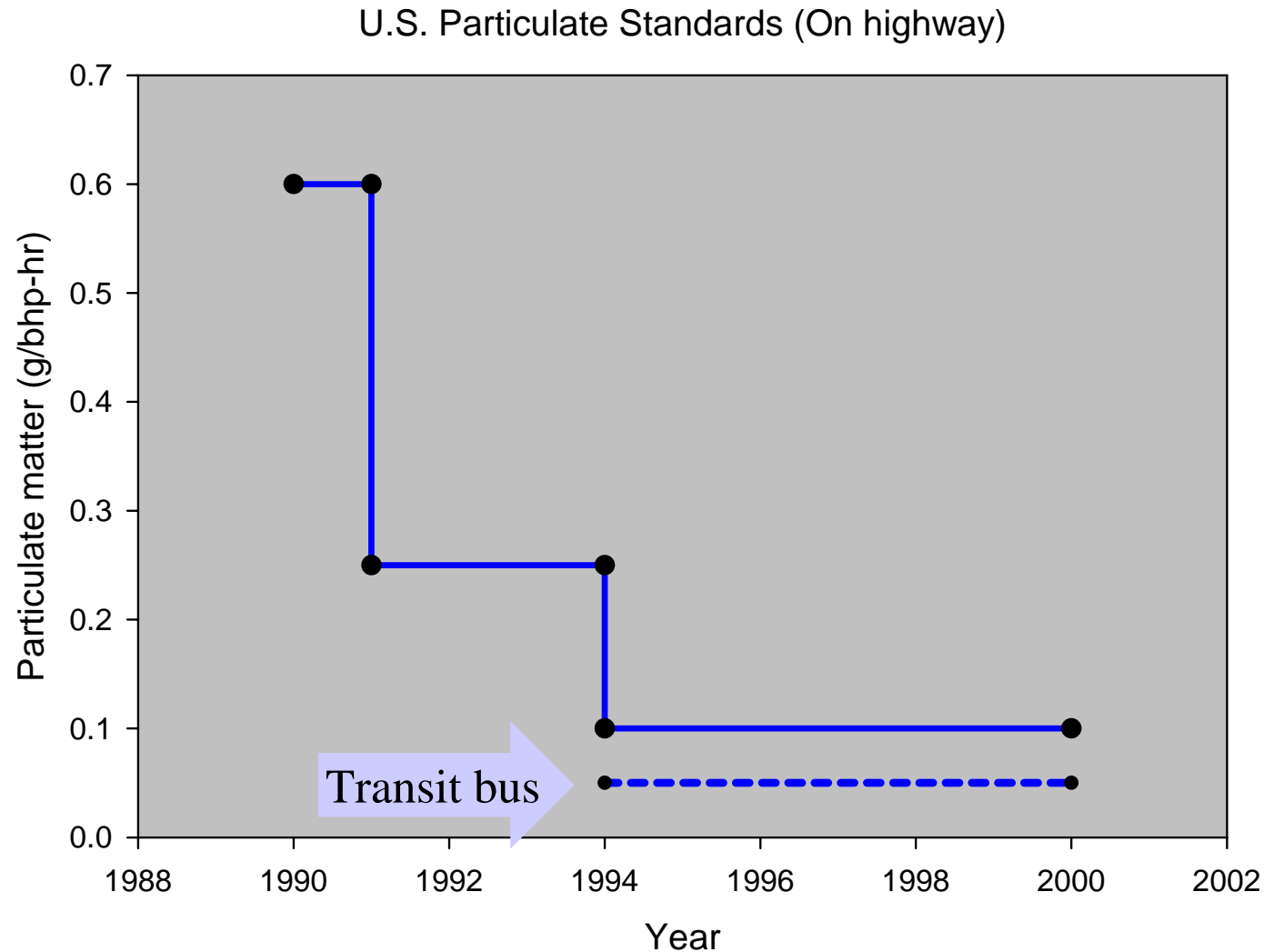


Tests on Cummins full-flow dilution tunnel

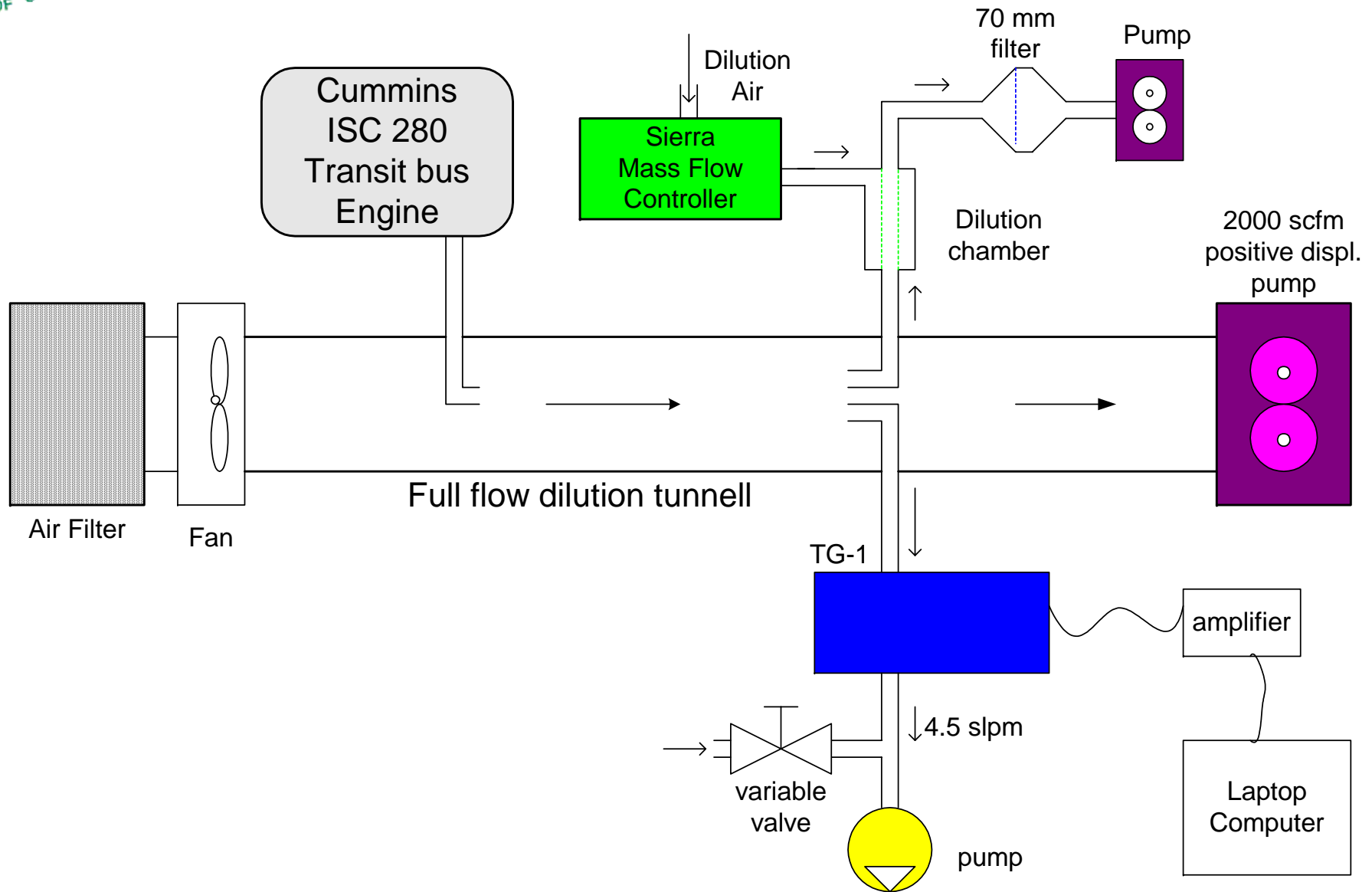




The Engine tested had to satisfy the most stringent of PM emission standards



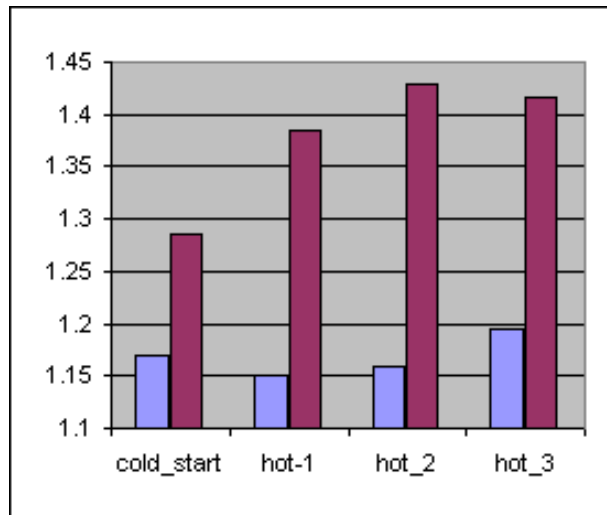
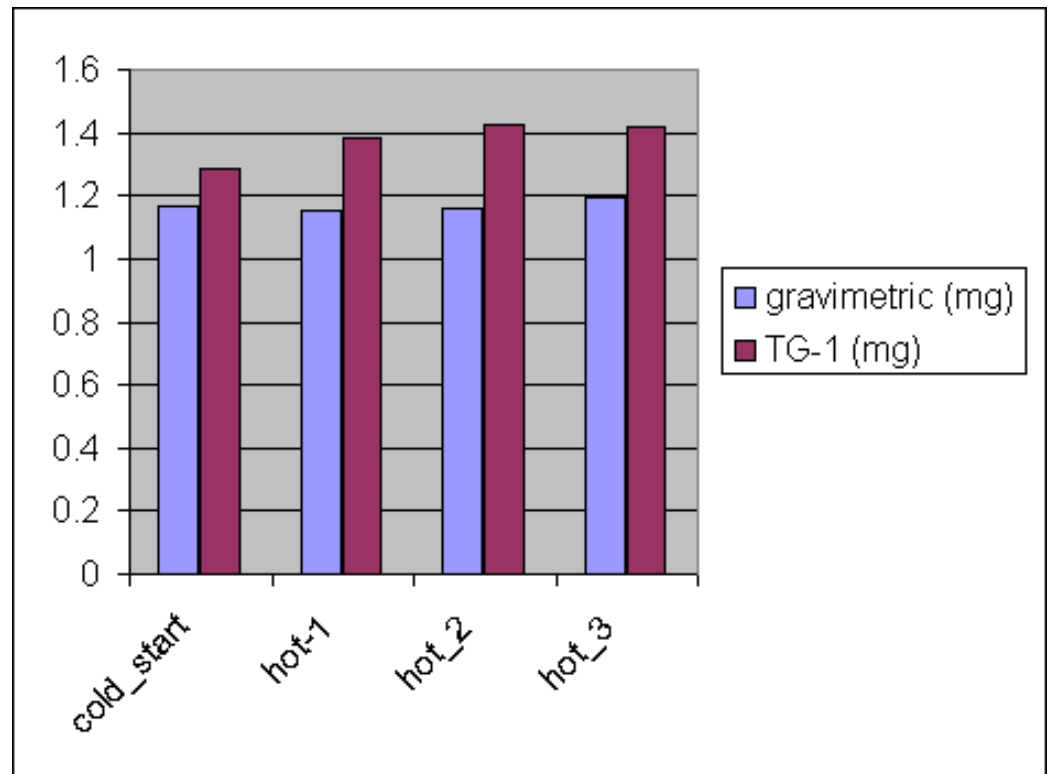
Cummins' full-flow dilution setup





Gravimetric vs. TG-1 over the transient cycle

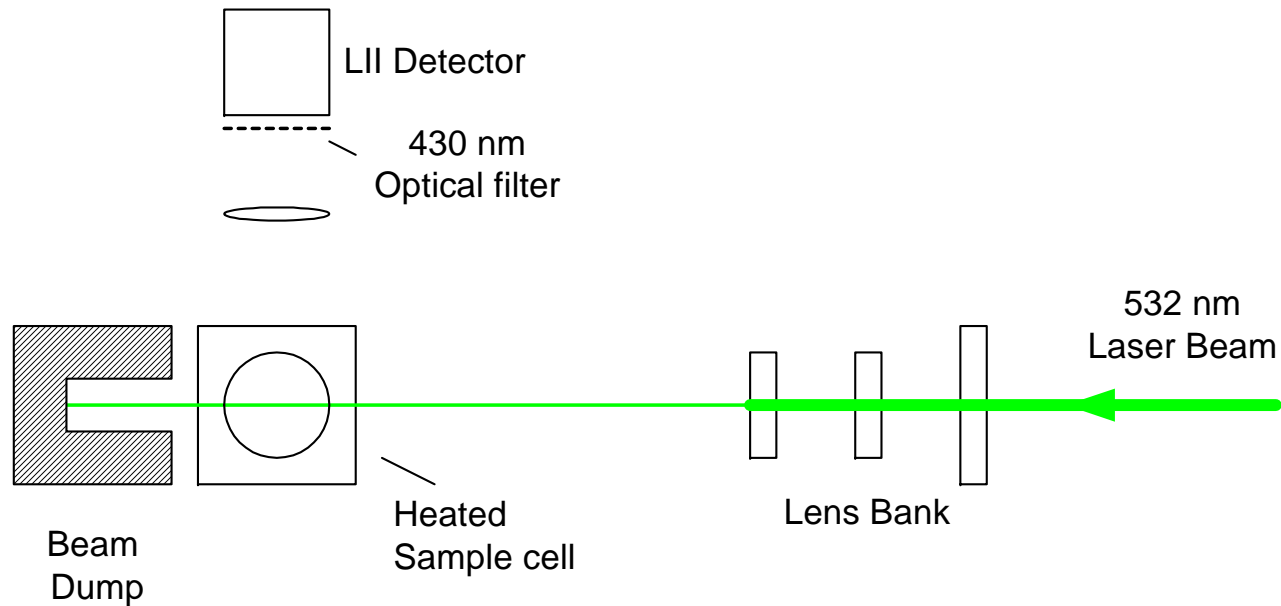
	Total flow (m3)	Gravimetric (mg)	TG-1 (mg)
Cold start	1.1646	1.17	1.285
Hot start 1	1.1684	1.15	1.385
Hot start 2	1.16294	1.158	1.428
Hot start 3	1.16334	1.194	1.416



- In these limited set of tests the agreement is encouraging.
- Cummins desires agreement within **0.01 mg**

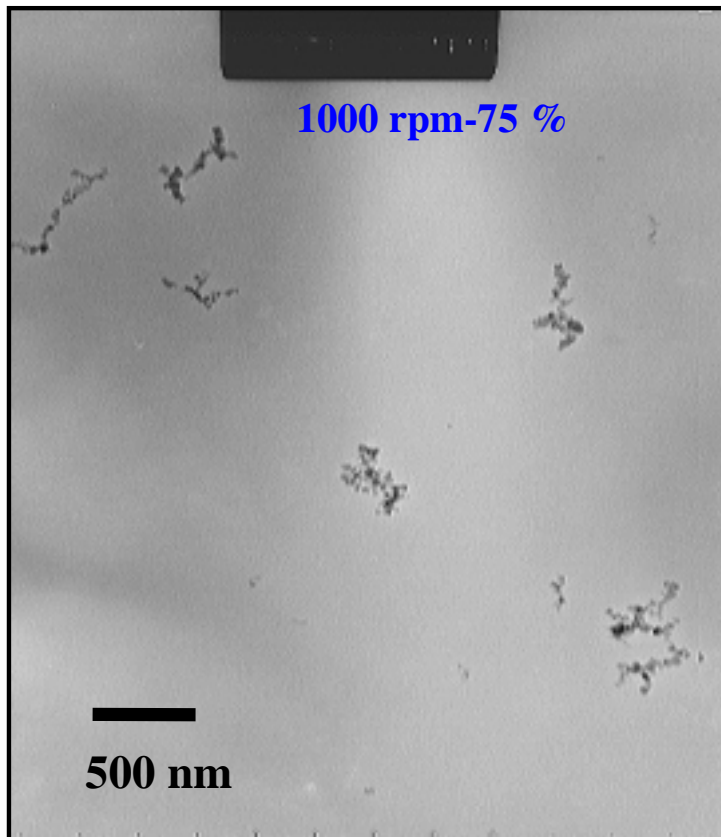


Ongoing Effort: Develop capability to measure Particle number density and aggregate size

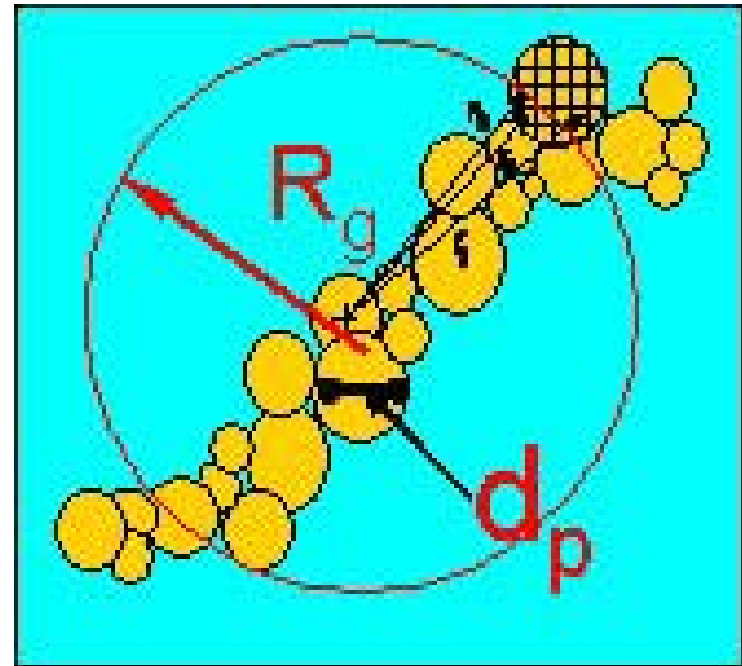


Rayleigh scattering signal in combination with LII signal provides aggregate particle size and number information

Validation of particle size to be performed using TEM morphology studies



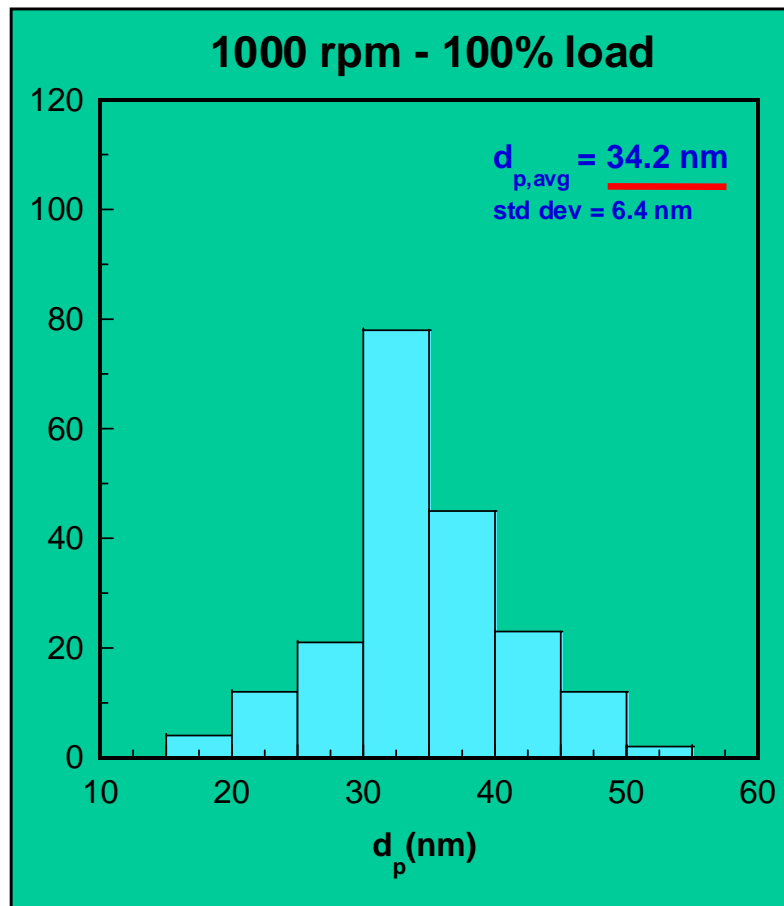
- Stretched chain-like particles
- 17,000 magnification



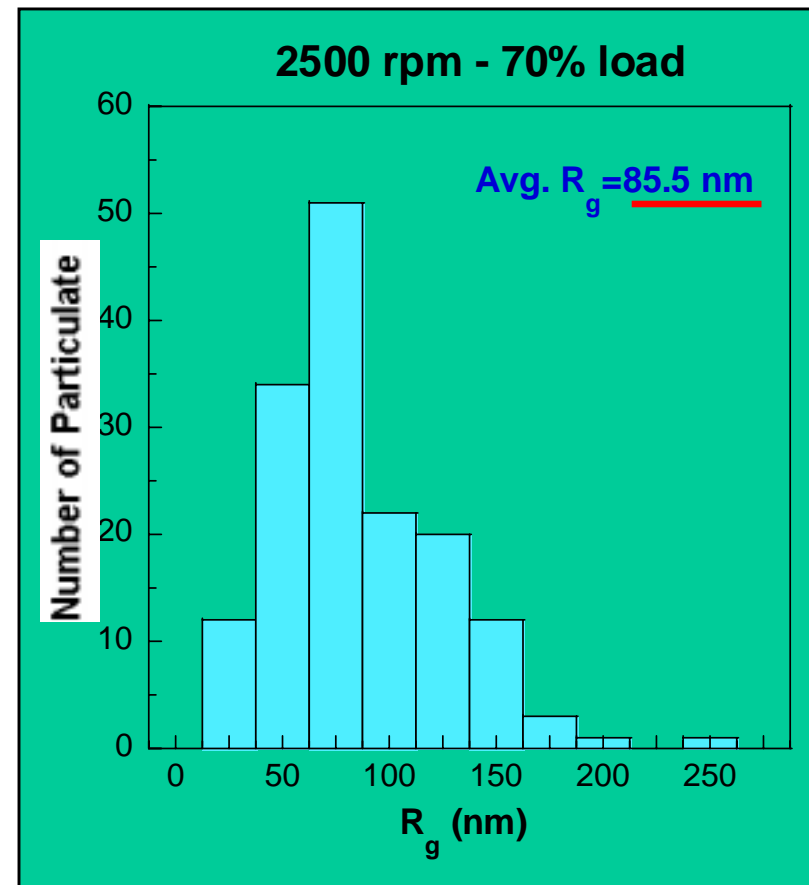
K. O. Lee, Poster session



Such studies yield very accurate particle size information



Primary particle size



Aggregate particle size



TG-1 may help develop control strategies to lower the NO_x – soot tradeoff

